

# TIME TRANSFER USING GPS CARRIER PHASE METHODS

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## Abstract

We have conducted several time-transfer experiments using the phase of the GPS carrier rather than the code, as is done in current GPS-based time transfer systems. We used data from geodetic quality "off-the-shelf" dual-frequency GPS receivers, where up to 8 satellites can be simultaneously observed.

We connected two GPS receivers to two different atomic clocks at NIST. The antennas connected to the receivers were separated by about 40 m. The time difference between the clocks connected to the GPS receivers was estimated using weighted least-squares methods and carrier phase data. These relative clock estimates were then compared with the NIST time-scale system. We find agreement between the two methods of 55-80 picoseconds over periods of a week.

## INTRODUCTION

Soon after the Global Positioning System was developed, the geophysical community began to apply it to numerous scientific problems, including plate tectonics, post-glacial rebound, interseismic deformation, and volcano monitoring.<sup>[1]</sup> The size of signals associated with these phenomena can be as small as 1 mm/yr. In order to address their science objectives, geophysicists have long been involved in research to improve the accuracy of GPS. When it became clear that their scientific goals required greater orbit accuracy, the geophysical community and their geodetic colleagues developed a global continuously operating GPS network. Data from this network are used to provide extremely accurate GPS ephemerides. Along with model improvements and careful reference frame definition, the accuracy of GPS position estimates now approaches one centimeter over averaging periods of a day.<sup>[2]</sup> Sub-centimeter horizontal precisions are routinely reported for distances of several thousand kilometers.<sup>[3]</sup> These achievements were made using the GPS carrier phase observable. The objective of this paper is to investigate the resolution of GPS carrier phase methods for time transfer.

## ESTIMATION

The GPS carrier phase observable  $\Delta\phi_r^s$  of wavelength  $\lambda$  can be written as:<sup>[4]</sup>

$$-\Delta\phi_r^s\lambda = \rho + c\delta^s - c\delta_r + N\lambda + \rho_t - \rho_i + \rho_m + \epsilon \quad (1)$$

where subscript  $r$  refers to the receiver and superscript  $s$  denotes the satellite.  $\rho$  is the geometric range, or  $|\vec{X}^s - \vec{X}_r|$ , where  $\vec{X}^s$  is the satellite position at the time of signal transmission and  $\vec{X}_r$  is the receiver position at reception time. Proper determination of  $\rho$  requires precise transformation parameters between the inertial and terrestrial reference frames, i.e. models of precession, nutation, polar motion, and UT1-UTC.  $\rho_t$  and  $\rho_i$  are the propagation delays due to the troposphere and ionosphere and  $\rho_m$  is the multipath error.  $\epsilon$  represents unmodelled errors and receiver noise. Since the GPS receiver only tracks the fractional phase, an integer bias,  $N$ , must be introduced to the model equation. This bias is also known as the carrier phase ambiguity.  $\delta^s$  and  $\delta_r$  are the satellite and receiver clock errors. An equivalent model equation can be derived for the pseudorange or "code" observable with several important distinctions. Pseudorange is not biased and so  $N$  is not estimated. The magnitude of the ionospheric delay is the same, but opposite in sign. The most significant pseudorange limitation is that the  $\epsilon$  term is nearly 100 times larger than for carrier phase.

The ionospheric delay can be effectively removed by combining the two GPS frequencies. The remaining parameters,  $\delta^s$ ,  $\delta_r$ ,  $\vec{X}^s$ ,  $\vec{X}_r$ ,  $\rho_t$ , and  $N$  must be estimated or known *a priori*. The model equation can be linearized and solved using weighted least squares. We used the GIPSY software to solve these equations.<sup>[5]</sup> Parameter estimation in GIPSY is carried out using a Square Root Information Filter (SRIF) algorithm described in [6]. Both satellite and receiver clocks are estimated at each data epoch relative to a reference receiver clock. The clock estimates are uncorrelated from epoch to epoch. The satellite coordinates  $\vec{X}^s$  are taken from the IGS service, with a radial accuracy of 5-10 cm.<sup>[7]</sup> The IGS analysis includes GPS data from 50 or more GPS receivers around the world. We estimate the wet tropospheric path delay at zenith as a time-dependent parameter with a random walk noise model.<sup>[8]</sup>

## RESULTS

Over short baselines, most geodetic parameters, including clocks, are insensitive to orbit error. This is also true of atmospheric conditions, which are common to both antennas for a short baseline. The limiting error sources in this case are likely to be multipath and receiver noise.

Two geodetic quality GPS receivers were connected to NIST Clock 16 and NIST Clock 21. Clock 16 is a hydrogen maser and Clock 21 is a cesium standard. Each GPS antenna was mounted to the roof of the NIST facility. The distance between the antennas was approximately 40 meters. The receivers were operated continuously for 28 days at a data interval of 30 seconds. Parameter estimation over short distances includes the behavior of Clock 21, carrier phase ambiguities, and the coordinates of each antenna. The carrier phase ambiguity bias terms were resolved.<sup>[9]</sup> Clock 16 was treated as the reference clock and its time-varying behavior was not estimated. There was no direct connection between the GPS receivers. All GPS estimates of the clocks are based on a full analysis of the GPS carrier phase observables.

We have made independent measurements of Clock 16 and Clock 21 using a special hardware system that looks like a group of time interval counters (TIC). These data were acquired automatically every

12 minutes. The difference between Clock 16 and Clock 21 as measured by the TIC system is shown in Fig. 1.

Over the 28 days of this experiment, the GPS receiver connected to Clock 21 lost lock on all satellites 3 times. This resulted in minimal data loss (5-15 minutes), but did introduce a bias into our solutions. A geodetic GPS receiver is programmed by the manufacturer to "reset" its internal clock whenever the receiver loses lock on all satellites. The receiver sets its clock by the GPS constellation in view at that time. Because of selective ability this bias can be as large as 300 nsec. It is this internal clock that is used to define the carrier phase observable. With appropriate modifications to the receiver, this reset can be calibrated.

In Fig. 2 we demonstrate the advantage of using carrier phase data over pseudorange data. In each time series we have subtracted the TIC clock measurements as truth. Thus, we are showing the residual agreement for the measured difference between Clock 16 and Clock 21. In Fig. 2a we used only pseudorange data. The residuals show peak-to-peak scatter of 10 nsec, with a RMS agreement over the 7-day period of 2.3 nsec. The large daily signature in the pseudorange data is associated with multipath. Since a GPS satellite will appear 4 minutes earlier each day, we expect multipath to have a 23 hour 56 minute period. In Fig. 2b we used carrier phase data. The residual RMS agreement using carrier phase data is 55 picoseconds.

In Fig. 3 we summarize the results for our 28-day experiment. We have plotted the residual of the difference between the GPS estimates and the TIC values for the 4 separate sections of data. Each section is plotted against its own mean. The weighted RMS residuals for the 4 sections range from 55 to 81 picoseconds. At this scale we can see that carrier phase data are also affected by multipath.

## CONCLUSIONS

We have demonstrated 55-81 picosecond accuracy for time transfer over short distances over periods of a week. The dominant error appears to be multipath. The effect of multipath can be reduced by careful site selection. To achieve 50 picosecond time transfer accuracy, geodetic quality dual frequency receivers with 8 or more channels must be used and ambiguity resolution is required.

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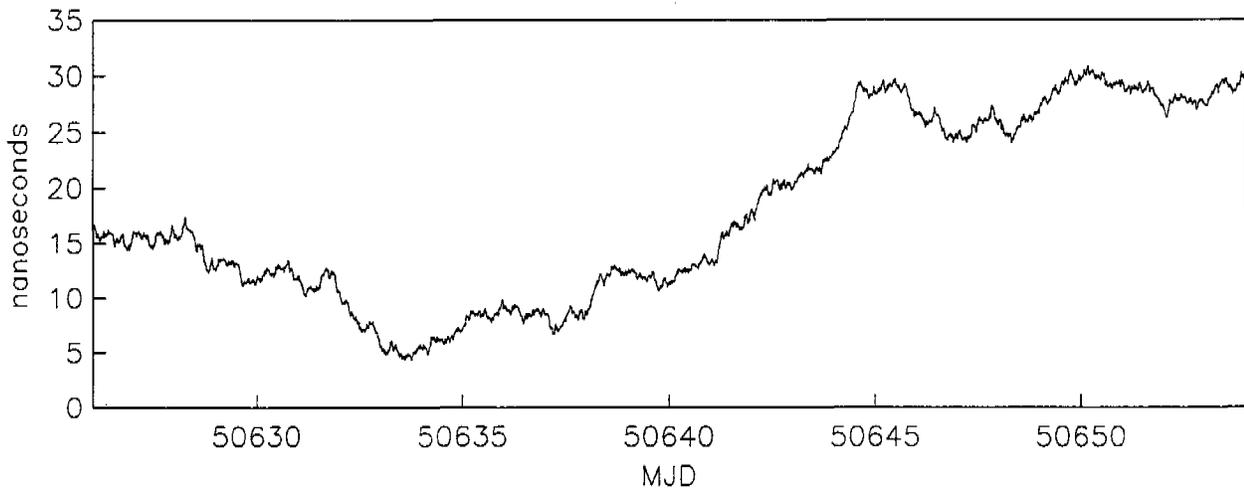


Fig. 1: Measured difference between NIST Clock 16 and NIST Clock 21 during GPS experiment using time interval counters.

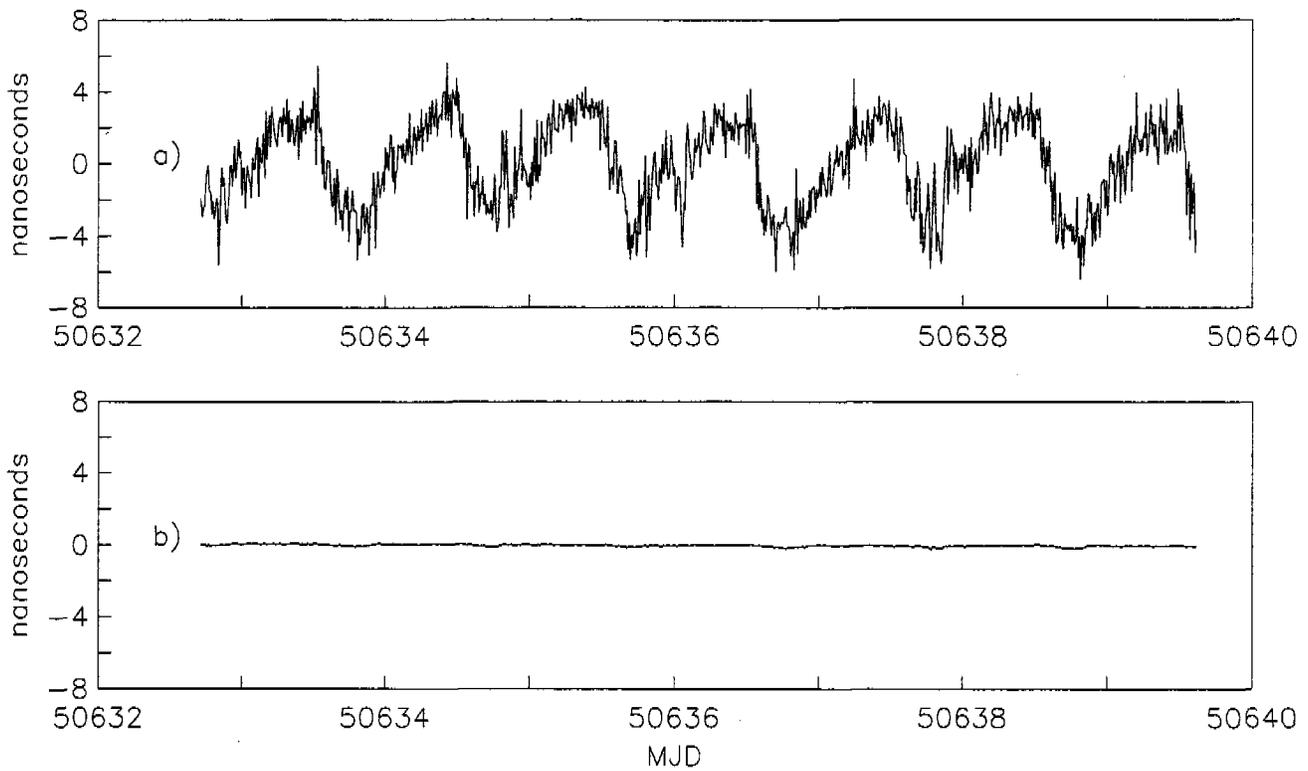


Fig. 2: The residuals between GPS estimates of the Clock 16-21 difference and the measured difference taken from Fig. 1 for a) pseudorange data and b) carrier phase data. The pseudorange RMS agreement is 2.38 nanoseconds. The carrier phase RMS agreement is 55 picoseconds.

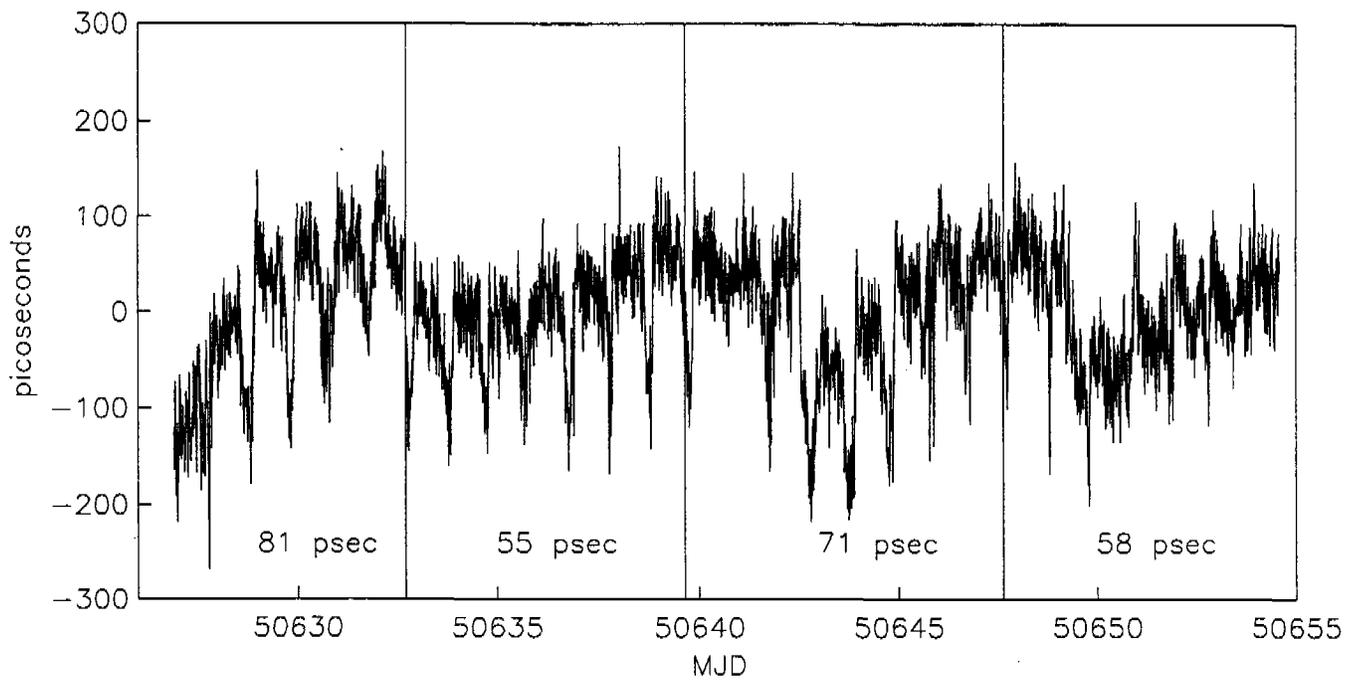


Fig. 3: The residuals between GPS estimates of the Clock 16-21 difference and the measured difference from Fig. 1 for 28-day period. Each vertical line represents independent analysis of data from the two GPS receivers. The RMS agreement for each data segment is shown below the data.

## Questions and Answers

MARC WEISS (NIST): How do you know that those are diurnal effects or multi-path? Could they perhaps be ionosphere?

KRISTINE LARSON (UNIVERSITY OF COLORADO): No, they are not ionosphere. I am using a dual frequency correction for the ionosphere. These are geodetic quality, dual frequency geodetic receivers, and the ionospheric errors respectively reduce to a random error by doing that.

MARC WEISS: Do the satellites have biases that differ from one satellite to the other in the L1 - L2?

KRISTINE LARSON: Not the ionosphere. It is definitely not the ionosphere. There conceivably could be atmospheric effects, but it is not the ionosphere. You can check that by doing elevation cut-off tests and things like that. Multi-path will depend on those elevation cut-offs or how low you look in the sky; and so it is multi-path, but I did not demonstrate it here. I just said it was.

GERARD PETIT (BIPM): What about variations in the antenna delay and so on? You do not seem to experience such delays even in the long baseline experiments. In the short baseline, it is conceivable because the two sets of equipment are similar, should have similar variations. But the long baseline is also very --

KRISTINE LARSON: Delays in the antenna, temperature delays and things like that?

GERARD PETIT: Yes.

KRISTINE LARSON: Yes, I think that would be interesting to look at over a longer period of time. This was just a three-week experiment, and that is the next thing to look at. This looks very promising, and to do a proper comparison you have to look over a long enough period to see all the potential problems. I think that is a good thing to look at.

JOHN LUCK (ORRORAL GEODETIC OBSERVATORY): I understand that Ashtech are developing a system whereby the time is inserted from your local clock into the receiver. Would that get rid of the jumps that you were noticing?

KRISTINE LARSON: Right - Yes!

JOHN LUCK (ORRORAL GEODETIC OBSERVATORY): Do you know the status of the Ashtech development?

KRISTINE LARSON: I have heard that about Ashtech as well. In fact, I have heard they did it for the University of Bern. I think the TurboRogue folks could do it, too, if they wanted to; and in the meantime, I talked to the people at JPL, as most of you know, they helped develop the TurboRogue. They gave me a way to calibrate it without any change, but it would be easier if the manufacturer would just do it.

CLAUDINE THOMAS (BIPM): I can say that three of these new Ashtech's at 12-T, adapted to time, are now in operation; one at NPL in the UK, one at LPTF at the Paris Observatory, which is just beginning its work; and one at BIPM which arrived last Monday, and of course we do not have any data yet. But it will be in operation.

KRISTINE LARSON: These do not reset? Okay - Good!